Run-11 RHIC Polarimetry Analysis

version 0.4

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Abstract

We present results on the measurement of polarization of proton beams in RHIC run 11.

Contents

1 Beam polarization

In the 2011 run every attempt was made to collect good data with all RHIC polarimeters in every fill. As the result of this effort, in most of the 2011 fills we have several measurements of the beam polarization $P_{\text{crb}}^{(\text{p})}$ (from context, p = B1U, Y1D, B2D, Y2U; p = U, D; or p = B, Y) obtained with the p-Carbon polarimeters and the average fill polarization, P_{jet}, obtained with the H-jet polarimeter. Most of the p-Carbon measurements were "sweep" measurements thus providing us with corresponding horizontal $R_v^{(\text{p})}$ and vertical $R_h^{(\text{p})}$ beam profiles. From the "sweep" measurements we calculate the fill average polarization[1] $\overline{P_{\text{crb}}^{(\text{p})}}$ with the corresponding statistical error $\Delta\overline{P_{\text{crb}}^{(\text{p})}}$, and the fill average polarization profiles $\overline{R_v^{(\text{p})}}$ and $\overline{R_h^{(\text{p})}}$ for each p-Carbon polarimeter.

The absolute H-jet polarimeter provides a direct measurement of the beam polarization P_{jet} whereas the polarization $P_{\text{crb}}^{(\text{p})}$ is initially calculated using predictions for the p-Carbon analyzing power based on the 2004 run data [?]. We choose not to rely on these estimates but instead we correct on average the p-Carbon numbers to the H-jet value in each fill. The normalization factor $k_{\text{jet/crb}}^{(\text{p})}$ is defined by the average ratio over all fills as:

$$k_{\text{jet/crb}}^{(\text{p})} = \left\langle \frac{P_{\text{jet}}}{\overline{P_{\text{crb}}^{(\text{p})}}} \right\rangle_{\text{fills}} . \tag{1}$$

It will be shown later that the normalization to the H-jet value can also account for some systematic effects associated with the measurement by the p-Carbon polarimeters while still allowing one to benefit from the larger statistics. We calculate the correction factors for each of the p-Carbon polarimeters individualy. Formally, the corection for the central value and the statistica error can be written as:

$$\overline{P^{(\text{p})}} \equiv \overline{P_{\text{crb}}^{(\text{p})}} \times k_{\text{jet/crb}}^{(\text{p})} \qquad \text{and} \qquad \Delta\overline{P^{(\text{p})}} \equiv \Delta\overline{P_{\text{crb}}^{(\text{p})}} \times k_{\text{jet/crb}}^{(\text{p})} \tag{2}$$

1.1 Beam polarization in a fill

In general, we do not see a reason for using measurements from either upstream or downstream polarimeter alone. Therefore, we calculate the final fill polarization, $\overline{P}$, for each beam by calculating the weighted average of the two p-Carbon polarimeters in the ring:

$$\overline{P} = \frac{\sum\limits_{\text{p=U,D}} \overline{P^{(\text{p})}} w^{(\text{p})}}{\sum\limits_{\text{p=U,D}} w^{(\text{p})}} \qquad \text{and} \qquad \left(\Delta\overline{P}\right)^2 = \left(\sum_{\text{p1,p2=U,D}} (V^{-1})_{(\text{p1p2})} \right)^{-1} , \tag{3}$$

where the weights $w^{(\text{p})}$ are defined through a covariance matrix V as:

$$w^{(\text{p})} = \frac{\sum\limits_{\text{p1=U,D}} (V^{-1})_{(\text{p1p})}}{\sum\limits_{\text{p1,p2=U,D}} (V^{-1})_{(\text{p1p2})}} \tag{4}$$

In case of uncorrelated errors on $\overline{P^{(\text{U})}}$ and $\overline{P^{(\text{D})}}$ the covariance matrix is diagonal with $V_{(\text{pp})} = \left(\Delta\overline{P^{(\text{p})}}\right)^2$ and weights $w^{(\text{p})} = 1/\left(\Delta\overline{P^{(\text{p})}}\right)^2$.

[1]The better way is to calculate a luminosity weighted average.

The physicists analyzing the data from the collider experiments STAR and PHENIX are interested in the beam polarization in collisions. This polarization takes into account the intensity profile of the both beams:

$$\overline{P}_{\text{coll}} = \frac{\iint \overline{P}(x,y) I^{(\text{B})}(x,y) I^{(\text{Y})}(x,y) dxdy}{\iint I^{(\text{B})}(x,y) I^{(\text{Y})}(x,y) dxdy} \tag{5}$$

Assuming the polarization and intensity profiles have a gaussian shape the relation between $\overline{P}$ and $\overline{P}_{\text{coll}}$ can be simply written as:

$$\overline{P}_{\text{coll}} = \overline{P} \times k_{\text{coll}} \qquad \text{with} \qquad k_{\text{coll}} = \frac{\sqrt{1+\overline{R_h}}\sqrt{1+\overline{R_v}}}{\sqrt{1+\frac{1}{2}\overline{R_h}}\sqrt{1+\frac{1}{2}\overline{R_v}}}. \tag{6}$$

In the calculation of the profile correction factor k_{coll} we use the profile ratios $\overline{R_h}$ and $\overline{R_v}$ averaged over the fill. These quantities are extracted from the fit [**?**].

It is not uncommon for the analyzers to combine a number of fills in order to calculate the average polarization. While the statistical uncertainty is always independent in distinct measurements a special care should be taken in calculation of separate components of the total systematic uncertainty on the final average. In the following we discuss the systematic uncertainties and their correlation in details.

2 Systematic Uncertainties

In this section we discuss the systematic uncertainties associated with the polarizatin measurement by both the p-Carbon and H-jet polarimeters. Not all of the discussed uncertainties directly enter the final result as some can be indirectly accounted for through a proper normalization.

2.1 Uncertainties on p-Carbon polarization

It is clear that due to normalization of the p-Carbon fill average to the H-jet the final uncertainty on $\overline{P^{(\text{p})}}$ directly depends on the precision of the H-jet measurement itself. We distinguish the following three sources of systematics associated with the measurement by the H-jet polarimeter.

Normalization to H-jet (accuracy) As an estimate for this uncertainty, Δ^{norm}, we use the statistical uncertainty $\Delta k^{(\text{p})}_{\text{jet/crb}}$ on the normalization factor $k^{(\text{p})}_{\text{jet/crb}}$. It is a global uncertainty that fully correlates across individual fills. Note that for a single fill Δ^{norm} is simply equal to the statistical error on the H-jet measurement while it decreases as $\frac{1}{\sqrt{N}}$ when the number (N) of considered fills increases. The best estimate of Δ^{norm} is calculated using the set of all available fills in this run. The ratio of the H-jet to the p-Carbon values is shown in Figure 1 and the normalization factors with respect to the polarization calculated with the 2004 analyzing power are shown in Table 2.

We regard this error as correlated between the two polarimeters in each ring but uncorrelated across the yellow and blue rings. The relative uncertainties are listed in Table 3.

Normalization to H-jet (precision) As seen in Figure 1 the distribution of ratios $K \equiv P_{\text{jet}}/\overline{P^{(\text{p})}_{\text{crb}}}$ by fill significantly deviates from a constant for all four polarimeters (although Y2U has the least significant disagreement). We attribute this inconsistency, σ^{norm}, to systematic effects seen in the p-Carbon polarimeters. Specifically, an essentially unknown orientation of the target to the proton

Table 1: Normalization factors with respect to the measurements utilizing the 2004 run predictions.

	$k^{(p)}_{\text{jet/crb}} \pm \Delta k^{(p)}_{\text{jet/crb}}$
B1U	$(0.998 \pm 0.011 \times 0.936) = 0.934$
Y2U	$(1.000 \pm 0.011 \times 0.933) = 0.933$
B2D	$(1.027 \pm 0.013 \times 1.030) = 1.058$
Y1D	$(1.005 \pm 0.015 \times 0.904) = 0.909$

beam in each measurement can lead to variations in carbon energy losses in the target. Another contribution perhaps comes from a nonuniform motion of the target through the beam. We assume that the nature and the scale of such systematic effects do not vary significantly from fill to fill and thus, we can estimate the overal systematic contribution by solving the following equation for σ^{norm}:

$$\frac{1}{N} \sum_{i=\text{fills}} \frac{(K_i - k^{(p)}_{\text{jet/crb}})^2}{(\sigma^2_{K_i} + (\sigma^{\text{norm}})^2)} = 1 \tag{7}$$

We regard this error as uncorrelated across the polarimeters and individual measurements. The common relative uncertainties for all fills are listed in Table 3.

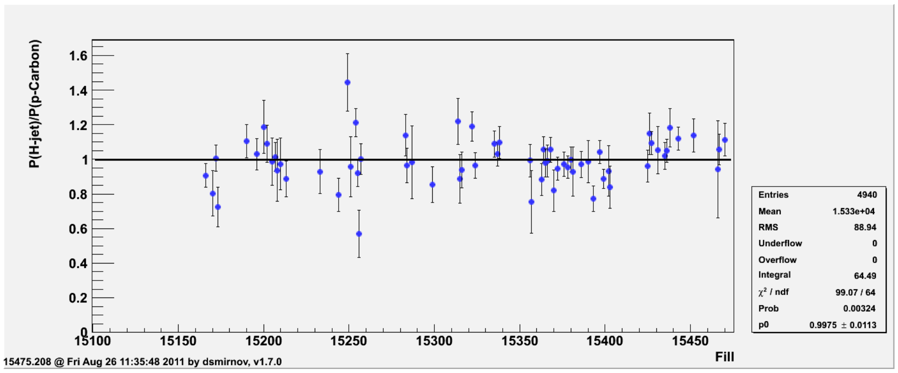
H-jet molecular background The average polarization values P_{jet} rely on the hydrogen jet target polarization as measured by a Breit-Rabi polarimeter. Prior to the 2011 run the jet target was believed to be contaminated with unpolarized molecular hydrogen H_2. In fact, a special study was carried out in 2004 to estimate the H_2 background in the hydrogen target [**?**]. The study has shown a contribuion of $\sim 3.7\%$ from H_2 lowering the typical polarization numbers of the H-target from $\sim 96\%$ to $\sim 92\%$. The total relative error associated with this measurement was estimated to be 2%. The latter directly propagates to the final polarization results via the correction of P_{jet} for the H_2 background.

In this run we observe that the total background to the H-jet can be significantly polarized thus the assumption that the molecular hydrogen is unpolarized is questionable. In the current analysis we use the uncorrected value of $\sim 96\%$ for the jet target polarization, however, we decided to keep the previously obtained $\Delta^{\text{mol}}_{\text{jet}} = 2\%$ for the 250 GeV proton beams.

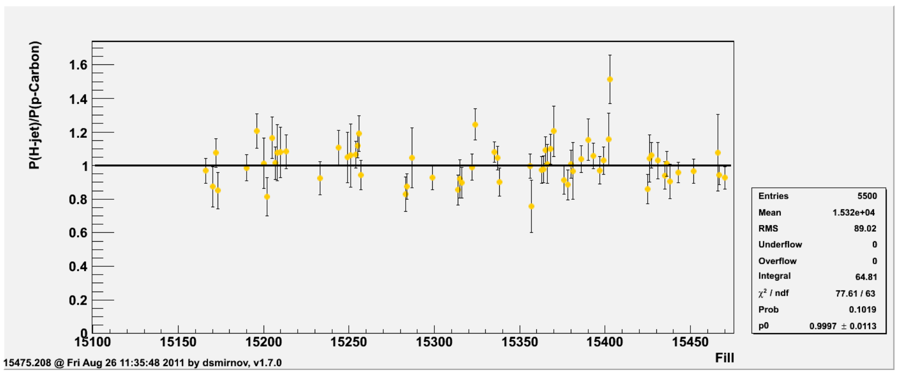
We regard this error as correlated between the yellow and blue beams and all four p-Carbon polarimeters. The relative uncertainties for all fills are listed in Table 3.

Total H-jet background The error $\Delta^{\text{bkg}}_{\text{jet}}$ represents the uncertainty on the total estimated background in the measurement of P_{jet}. While the major contributor is believed to be the H_2 in the target some other sources can contribute to the total background. For example, we do not know how much inelastic processes can contribute to our final sample. Also, since the H-jet measures polarization of the two beams simultaneously, one can imagine that there is a non-zero contribution from the back scattering from one beam contaminating the other. The backgound is estimated using the method of side bands in which the total count in the non-signal strips is extrapolated to the signal ones. We do not have an estimate of this unceratainty in 2011 (???), instead we use the value of 3% as was defined in the previous run.

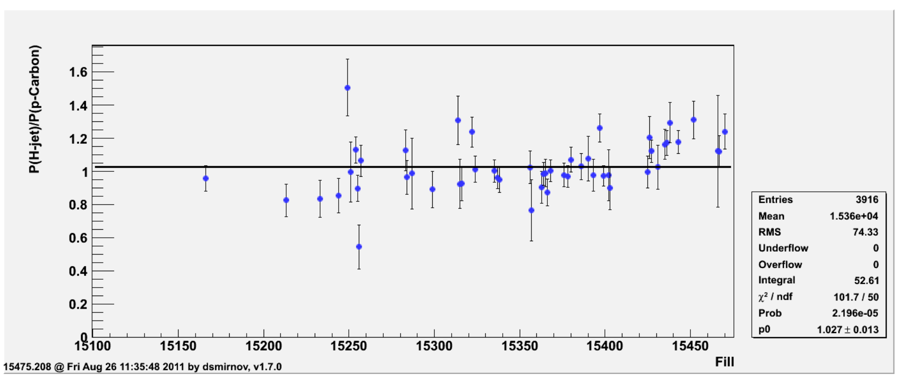
We regard this error as correlated between the yellow and blue beams and all four p-Carbon polarimeters. The relative uncertainties for all fills are listed in Table 3.



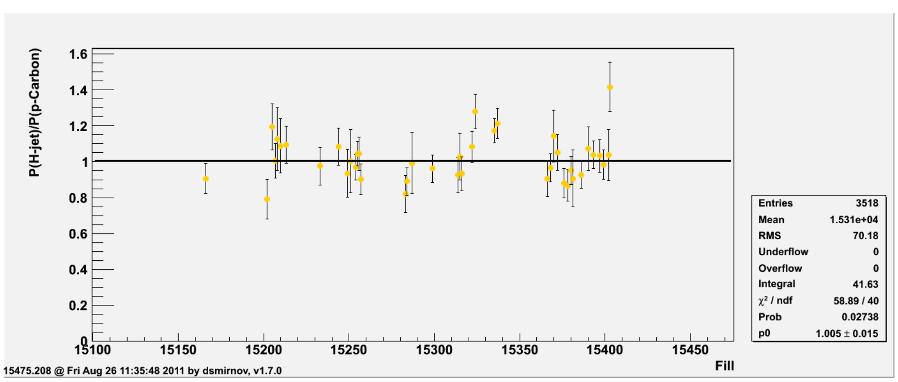
(a) Blue-1 Upstream



(b) Yellow-2 Upstream



(c) Blue-2 Downstream



(d) Yellow-1 Downstream

Figure 1: The ratio of P_{jet} and $\overline{P^{(\mathrm{p})}_{\mathrm{crb}}}$.

Polarization profile In the 2011 run we also observe a systematic difference in the central polarization values as determined directly from a standard sweep measurement and a corresponding value extracted from the polarization *vs.* intensity fit. The ratio of these two numbers for each fill is shown on Figure 2. This systematic effect is supported by the fact that the target may not exactly follow the uniform motion of the frame when crossing the beam. Instead, the target may be electrostatically attracted to the beam center causing an incorrect weighting of the events in the final data set. We believe that the polarization extracted from the fit represents a more accurate estimate of the true beam polarization. To quantify this inconsistency we introduce a scale factor $k^{(\mathrm{p})}_{\mathrm{prfl/swp}}$ defined as

$$k^{(\mathrm{p})}_{\mathrm{prfl/swp}} = \left\langle \frac{\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}}}{\overline{P^{(\mathrm{p})}_{\mathrm{crb}}}} \right\rangle_{\mathrm{fills}}, \tag{8}$$

where $\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}}$ is the polarization extracted from the polarization *vs.* intensity fit. The scale factors with the corresponding errors for each p-Carbon polarimeter are listed in Table 2. Similar to the estimation of systematic effects in the normalization to the H-jet we calculate both the precision of Δ^{prfl} and the precision σ^{prfl} of the non-statistical inconsistency.

Table 2: Normalization factors for the sweep measurements.

	$k^{(\mathrm{p})}_{\mathrm{prfl/swp}} \pm \Delta k^{(\mathrm{p})}_{\mathrm{prfl/swp}}$
B1U	0.9739 ± 0.0015
Y2U	0.9761 ± 0.0013
B2D	0.9859 ± 0.0017
Y1D	0.9863 ± 0.0013

We regard this error as uncorrelated across the polarimeters and individual measurements. The common relative uncertainties for all fills are listed in Table 3.

Summary The total uncertainty $\Delta\overline{P^{(\mathrm{p})}}$ on $\overline{P^{(\mathrm{p})}}$ is:

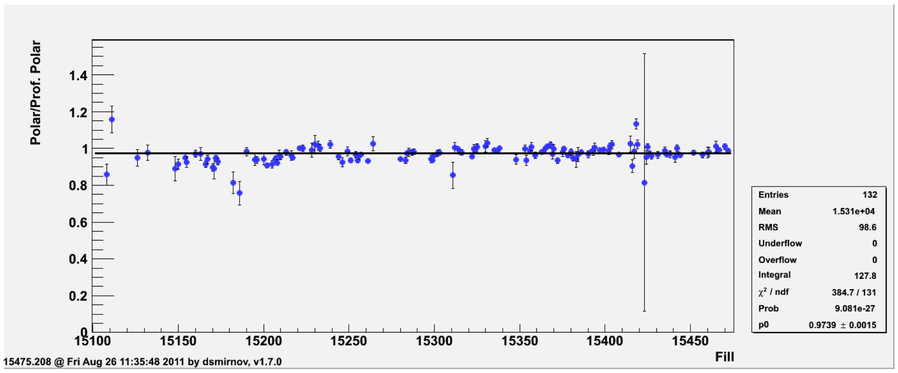
$$\frac{\Delta\overline{P^{(\mathrm{p})}}}{\overline{P^{(\mathrm{p})}}} = \underset{\mathrm{stat}}{\Delta} \oplus \frac{\Delta k^{(\mathrm{p})}_{\mathrm{jet/crb}}}{k^{(\mathrm{p})}_{\mathrm{jet/crb}}} \oplus \sigma^{\mathrm{norm}} \oplus \Delta^{\mathrm{mol}}_{\mathrm{jet}} \oplus \Delta^{\mathrm{bkg}}_{\mathrm{jet}}. \tag{9}$$

Note that we do not include the uncertainty due to inconsistent polarization profile measurements. The normalization of $\overline{P^{(\mathrm{p})}}$ to P_{jet} already accounts for most of the non-statistical variations.

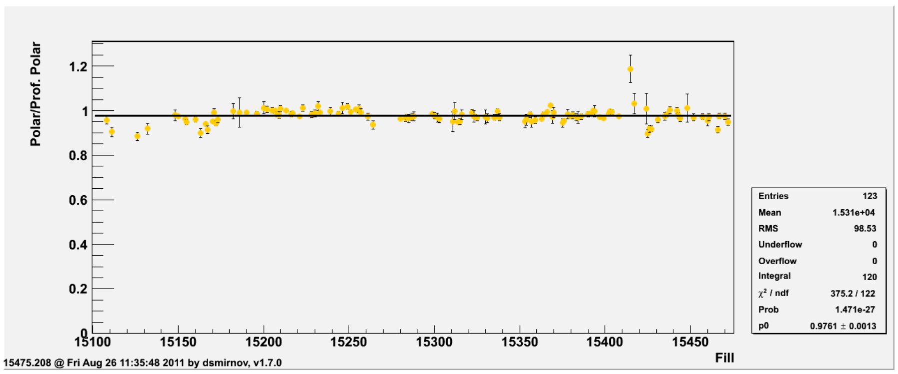
2.2 Uncertainties on beam polarization in a fill

According to our strategy outlined in Section 1.1 we estimate the final beam polarization $\overline{P}$ by calculating the weighted average of the numbers provided by the upstream and downstream polarimeters. In the fills where one of the polarimeters did not provide a measurement we use the result from the other one for the final beam polarization. The weights are calculated using only those components in (9) which do not correlate between the upstream and downstream polarimeters, namely, Δ_{stat} and σ^{norm}.

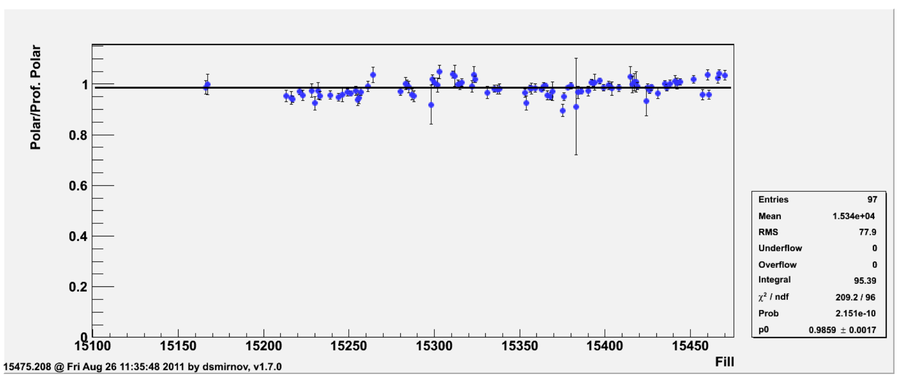
To check wether there is any systematics left in comparison of U vs. D I need to produce plots with the ratio of the average vs individual polarimeter.



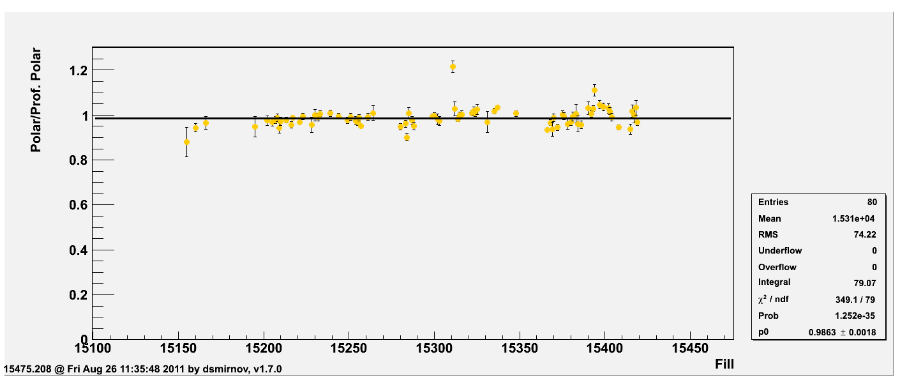
(a) Blue-1 Upstream



(b) Yellow-2 Upstream



(c) Blue-2 Downstream



(d) Yellow-1 Downstream

Figure 2: The ratio of $\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}}$ and $\overline{P^{(\mathrm{p})}_{\mathrm{crb}}}$.

Table 3: Summary of the relative systematic uncertainties for the p-Carbon polarimeters.

	B1U	**Y2U**	**B2D**	**Y1D**	**Correlation**
Δ^{norm}	6.6	6.7	5.8	9.1	
σ^{norm}	7.0	5.4	10.1	6.3	
$\Delta k^{(\mathrm{p})}_{\mathrm{jet/crb}}/k^{(\mathrm{p})}_{\mathrm{jet/crb}}$	1.1	1.1	1.2	1.5	
$\Delta^{\mathrm{mol}}_{\mathrm{jet}}$	2.0	2.0	2.0	2.0	
$\Delta^{\mathrm{bkg}}_{\mathrm{jet}}$	3.0	3.0	3.0	3.0	
Δ^{prfl}	2.6	2.4	1.4	1.4	
σ^{prfl}	2.9	2.2	1.9	3.5	
$\Delta k^{(\mathrm{p})}_{\mathrm{prfl/swp}}/k^{(\mathrm{p})}_{\mathrm{prfl/swp}}$	0.2	0.1	0.2	0.1	

Upstream vs downstream polarimeter In the fills where measurements from the two polarimeters in the same ring are available we observe non-statistical variations in the measurements even when they closely follow each other in time. At the moment, the observed fluctuations cannot be associated with a single source or a known difference in the devices therefore, we assign a systematic error, $\Delta^{\mathrm{U\ vs\ D}}$, on the fill average. We estimate the systematic uncertainty of this kind by calculating the difference between the fill average as measured by the two polarimeters. From Figure **??** the average difference is XXX. In order to cover most of our measurements we conservatively assign $\Delta^{\mathrm{U\ vs\ D}} = XXX$.
We regard this error as uncorrelated between the yellow and blue beams.

Summary If the averaging of the upstream and downstream polarimeters does not introduce any additional uncertatinty then:

$$\frac{\Delta\overline{P}}{\overline{P}} = w_U \times \frac{\Delta\overline{P^{(\mathrm{U})}}}{\overline{P^{(\mathrm{U})}}} \oplus w_D \times \frac{\Delta\overline{P^{(\mathrm{D})}}}{\overline{P^{(\mathrm{D})}}} \qquad \left(\oplus\Delta^{\mathrm{U\ vs\ D}}\right) \tag{10}$$

2.3 Uncertainties on beam polarization in collisions

In order to calculate the beam polarization in collisions $\overline{P}_{\mathrm{coll}}$ the average beam polarization $\overline{P}$ has to be reweighted taking into account the intensity profiles of both beams. Assuming a gaussian shape for both the polarization and intensity profiles the beam polarization given by (3) can be corrected by the scale factor k_{coll} from (6).

We define the uncertainty Δ^{R} as an error on the average fill polarization in collisions $\overline{P}_{\mathrm{coll}}$. This is not a systematic uncertainty but rather a propagation of the statistical uncertainty on the measured quantities $\overline{R_h}$ and $\overline{R_v}$ according to equations (6).

It is clear that the average beam polarization as measured by a p-Carbon polarimeter strongly depends on the shape of the beam and on the distribution of the polarization across the beam. For the gaussian shapes the relation between these quantities is trivial:

$$\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}} = \frac{P_{\mathrm{cntr}}}{\sqrt{1+R}}. \tag{11}$$

Due to the strong correlation between R and $\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}}$ one can attribute the observed non-statistical fluctuations (see Figure **??**) to both the true difference in the polarization from fill to fill and already accounted for systematic variation in the $\overline{P}$ (and therefore $\overline{\mathcal{P}^{(\mathrm{p})}_{\mathrm{crb}}}$). An Additional systematics in the measurement of R can come from the erroneous assumption on the shape of the beam profile although, the effect is believed to be small. At the moment, for the total uncertainty on $\overline{R_h}$ and $\overline{R_v}$ we plan to use only the statistical component extracted from the polarization vs. intensity fit leaving the estimation of the additional systematic effects to the future analysis.

We regard Δ^{R} as uncorrelated between the yellow and blue beams.

Summary For the sources of systematic uncertainties discussed above the total errors on the average fill polarization can be written as:

$$\frac{\Delta\overline{P}_{\mathrm{coll}}}{\overline{P}_{\mathrm{coll}}} = \frac{\Delta\overline{P}}{\overline{P}} \oplus \Delta^{\mathrm{R}} \tag{12}$$

2.4 Average polarization in a set of fills

For the average over a subset of selected fills we have:

$$\frac{\Delta\left\langle\overline{P}\right\rangle_{\mathrm{fills}}}{\left\langle\overline{P}\right\rangle_{\mathrm{fills}}} = \Delta^{\mathrm{norm}} \oplus \Delta^{\mathrm{mol}}_{\mathrm{jet}} \oplus \Delta^{\mathrm{bkg}}_{\mathrm{jet}} \tag{13}$$

$$\frac{\Delta\left\langle\overline{P}_{\mathrm{coll}}\right\rangle_{\mathrm{fills}}}{\left\langle\overline{P}_{\mathrm{coll}}\right\rangle_{\mathrm{fills}}} = \Delta^{\mathrm{norm}} \oplus \Delta^{\mathrm{mol}}_{\mathrm{jet}} \oplus \Delta^{\mathrm{bkg}}_{\mathrm{jet}} \tag{14}$$

2.5 Uncertainty on single spin asymmetry

For single spin asymmetry measurements the experiments use the average of the yellow and blue beam polarizations $\frac{\langle P^{(\mathrm{B})}\rangle+\langle P^{(\mathrm{Y})}\rangle}{2}$. The total uncertainty on the sum is then calculated using the values in Table 3. Taking into account the proper correlation between the two beams we obtain:

$$\Delta = \frac{1}{2} \times (\Delta^{\mathrm{norm}})^{(\mathrm{B})} \oplus (\Delta^{\mathrm{norm}})^{(\mathrm{Y})} \oplus \left((\Delta^{\mathrm{mol}}_{\mathrm{jet}})^{(\mathrm{B})} + (\Delta^{\mathrm{mol}}_{\mathrm{jet}})^{(\mathrm{Y})}\right) \oplus \left((\Delta^{\mathrm{bkg}}_{\mathrm{jet}})^{(\mathrm{B})} + (\Delta^{\mathrm{bkg}}_{\mathrm{jet}})^{(\mathrm{Y})}\right) \tag{15}$$

2.6 Uncertainty on double spin asymmetry

Similarly, the double spin asymmetry measurements use the product of two beam polarization $\langle P^{(\mathrm{B})}\rangle \times \langle P^{(\mathrm{Y})}\rangle$. The total unceratainty in this case is:

$$\Delta = (\Delta^{\mathrm{norm}})^{(\mathrm{B})} \oplus (\Delta^{\mathrm{norm}})^{(\mathrm{Y})} \oplus \left((\Delta^{\mathrm{mol}}_{\mathrm{jet}})^{(\mathrm{B})} + (\Delta^{\mathrm{mol}}_{\mathrm{jet}})^{(\mathrm{Y})}\right) \oplus \left((\Delta^{\mathrm{bkg}}_{\mathrm{jet}})^{(\mathrm{B})} + (\Delta^{\mathrm{bkg}}_{\mathrm{jet}})^{(\mathrm{Y})}\right) \tag{16}$$